

VANET Coverage Analysis for GPS Augmentation Data in Rural Area

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Abstract: Enhanced position accuracy is key for modern navigation systems, location based services and applications based on Inter-Vehicle Communication (IVC). Position data are the foundation for deriving vehicle trajectories used for assessing a situation's criticality in vehicle safety. Thus, especially Advanced Driver Assistance Systems (ADASs) and integral safety applications benefit from nearby vehicles spreading their positions periodically with high accuracy. Positioning based on Global Navigation Satellite System (GNSS) measurements can be enhanced by established Cooperative Positioning (CP) methods like Real-Time Kinematic (RTK) and Differential GNSS (DGNSS). Conventional CP relies on positioning correction data from a third party, whereas this paper introduces a self-sufficient CP system based on Precise Point Positioning (PPP) and Vehicular Ad-Hoc Network (VANET) technology requiring no infrastructure. Furthermore, the data dissemination process and achievable coverage are analysed by a simulation study for a rural area in Bavaria, Germany. For this purpose, the simulation employs the European IVC protocol stack ITS-G5. While the general feasibility of this CP approach could be assured, some remaining issues regarding employed network protocols were discovered as well.

Keywords: Communication networks, Global positioning system, Vehicular ad hoc networks, Intelligent transportation system, Real time kinematic, Portable Base

1. INTRODUCTION

Solely in 2014, more than 1.4 million individuals were injured and more than 25,000 were killed on roads within the European Union (European Commission, Directorate General for Mobility and Transport, 2016). Improvements in the field of Advanced Driver Assistance Systems (ADASs) generally and applications for cooperative car safety in particular nourish hope to decrease the number of injured and killed people in road traffic. Cooperative Intelligent Transportation Systems (ITSs) applied to car safety benefit from the exchange of driving dynamics data and precise position data between vehicles (Huang and Tan, 2009). Compared to conventional environmental sensors, such as radar, there are two major gains: (a) no line-of-sight is needed for detecting another vehicle and (b) there is no blind spot, i.e. Inter-Vehicle Communication (IVC) can be regarded as a 360° field of view sensor. These advantages allow a vehicle to react 0.2s to 0.3s earlier on non-line-of-sight conditions, e.g. in a closed intersection scenario (Schwarz, 2012).

However, a vehicle's self-localization capabilities have to be better than lane-level accuracy for many of these applications, e.g. cooperative collision warning (Shladover and Tan, 2006). Global Navigation Satellite System (GNSS) measurements, e.g. from the Global Positioning System (GPS), are the predominant mechanism for absolute position determination today. Highly accurate positioning is possible with GNSS using methods like Differential GNSS (DGNSS) and Real-Time Kinematic (RTK), which are described in Section 2. These techniques rely on correction data from nearby, stationary reference stations. Providers of such correction data are only available in some countries and data is usually spread via cellular mobile communication. Of course, data providers as well as network operators charge for correction data and their transmissions. These costs set aside, there might exist dead spots where no correction data are available, which can be assumed more likely in rural areas where infrastructure thins out. Some states with extensive rural areas like Bavaria, a federal state of Germany, where more than 80 % of the territory are forests or agricultural areas (Bayerisches Landesamt für Statistik, 2015), are especially affected by the risk of dead spots. The achievable coverage for Bavaria is estimated in Section 3.1 assuming a self-sufficient Cooperative Positioning (CP) system, which disseminates GNSS augmentation data using

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a Vehicular Ad-Hoc Network (VANET) as described in Section 3.2. This CP system incorporates parking cars as portable reference stations generating correction data GNSS positioning. A more detailed assessment of the CP system's performance is based on the simulation model presented in Section 4. The performance is studied with respect to the timely provision of correction data for a destination area. For this purpose, the simulation results are assessed using a dedicated metric in Section 5.

2. PORTABLE RTK-GNSS REFERENCE STATIONS

Before a parked vehicle can act as RTK base station, which is called Portable Base in the following, its position has to be determined accurately. For this purpose Precise Point Positioning (PPP) is conducted by these vehicles. PPP is a GNSS measurement technique that enables position determination with an accuracy of few decimetres to centimetres (Gao, 2006). Compared to other GNSS measurement techniques, including RTK, no reference station is needed at the cost of a few hours of constant measuring effort until such highly accurate position calculations are achievable.

Usually, PPP operates on dual-frequency measurements, so frequency-dependant errors such as propagation delays through ionosphere can be mitigated. Errors like phase center variation and phase center offset are corrected by PPP as well. Additionally, clock and orbit products from the International GNSS Service (IGS) can be exploited (Heßelbarth and Wanninger, 2012). A few years ago, these data were only available for post-processing, but today IGS provides precise satellite orbits in real time with almost the same accuracy as the final products for post-processing. Compared to real time data, however, final clock products are still more precise by two orders of magnitude (IGS, 2009). Figure 1 gives an impression of the increasing precision over time based on PPP. The measurement was conducted near to the location ① of Figure 3. A building located north of the receiver masked satellites with an elevation angle below 30° . In this particular case, the vehicle could start acting as reference station by sending RTK correction data when its position is accurately determined after roughly 2.5 h.

Any other moving vehicle, called rover henceforth, may receive this RTK data, which consists, among others, of the reference station's observations and its position determined through PPP. The rover processes the received and its own dual-frequency observations by RTK calculations. For this purpose, double differences are used to eliminate all common-mode errors, which affect the rover's and base's measurements the same way if they are not more than 5 km to 10 km apart. The result of RTK calculation is the relative position between reference station and rover, called base line vector, with an accuracy of a few centimetres. Since the rover knows the position of the reference station in global coordinates, it is trivial for the rover to derive its own global position precisely in a final step. (Misra and Enge, 2010)

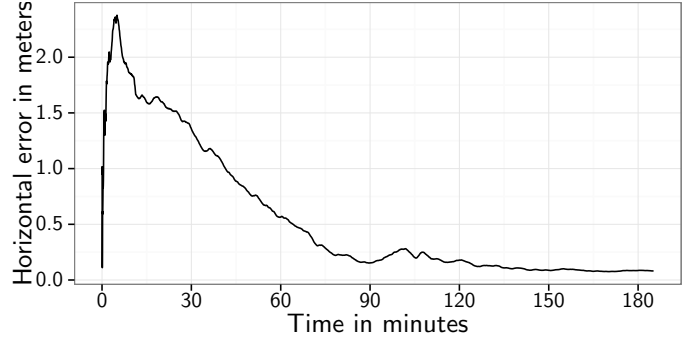


Fig. 1. Convergence of a PPP measurement

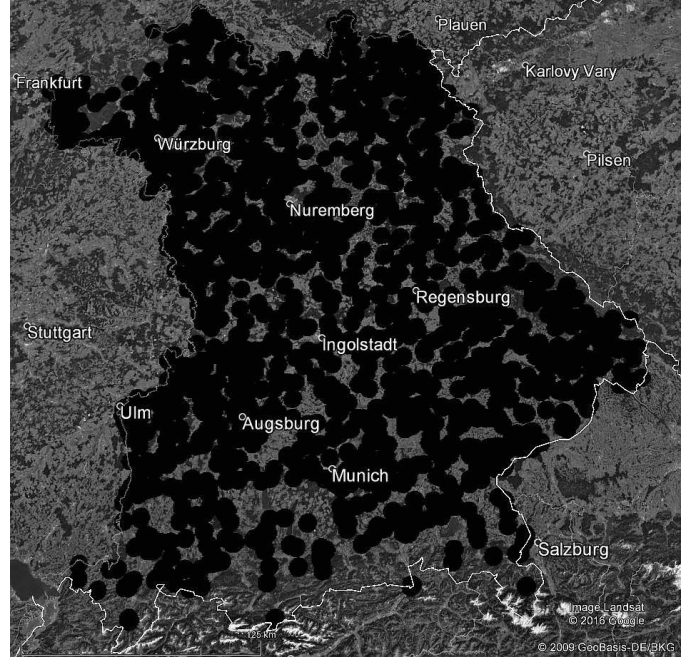


Fig. 2. Hypothetical coverage by Portable Bases in Bavaria

3. DISTRIBUTED RTK DATA PROVISIONING

3.1 Area Coverage

RTK is based on the fact that the common-mode errors in the surroundings of 5 km to 10 km affect all receivers the same way (Misra and Enge, 2010). Reference stations separated up to 50 km are sufficient in networked RTK because there exist several techniques to interpolate correction data between them, e.g. individualised Master-Auxiliary corrections (i-MAX), Virtual Reference Station (VRS), or Flächen-Korrektur-Parameter (FKP) standing for area correction parameter (Takac and Zelzer, 2008). All of these require a data processing center, though. On the contrary, the concept of Portable Bases is intended to operate without such a single point of failure. There is a snag to it, though, of requiring considerably more portable reference stations, which operate in a distributed manner.

This paper investigates the feasibility of supplying a whole area with RTK correction data using the Portable Base approach by the example of Bavaria. It is assumed that there is at least one parked vehicle suitable to act as Portable Base in each industrial area all over Bavaria: Commuters' vehicles are likely to be parked for several

hours in industrial areas so these vehicles can determine their exact position by PPP. The location of Bavaria's industrial areas can be extracted from SISBY (2014). Figure 2 is derived based on ambits of 5 km radius wherein common-mode errors can be corrected without data interpolation. According to this figure, 79 % of Bavaria can be supplied with RTK GNSS data from Portable Bases. Most gaps exist in the south towards the Alps where less industry is prevalent but more tourism. Therefore, despite of these uncovered areas on the map depicted in Figure 2, it is not unlikely that there are vehicles parked by tourists usable as Portable Bases as well.

3.2 Communication Link

Deduction of possible RTK correction data coverage from a GNSS algorithms' perspective is just one half, though. The other half is the actual transport of these data from the originating Portable Base to all rovers within a circumference of 5 km by means of wireless communication. Since a self-sufficient CP system is envisaged, the communication has to relinquish any infrastructure. Fortunately, no infrastructure is required for IVC using VANET technology. Consent with the investigated use case for Bavaria, communication is realised in the following using the European ITS-G5 protocols (ETSI, 2010).

Although the protocols are set, several aspects of the communication stack remain open. Starting with the stack's top layer, the encoding of correction data has to be decided. Basically, there are two format options: (a) Compact Measurement Record (CMR) (Talbot, 1996) including its extensions CMR+ and CMRx (Trimble, 2009) developed by Trimble. The other widely used standard (b) is RTCM (2013, Version 3.2) provided by the Radio Technical Commission for Maritime Services (RTCM) Special Committee (SC) 104, which is considered hereinafter. This standard recommends sending observation data of today's fully operational GNSSs (RTCM messages 1004, 1012 and 1230) with an interval of 1 s and static data (RTCM messages 1006 and 1033) with an interval of 10 s, which include e.g. base's antenna reference point. However, considering the dynamic environment of Portable Bases, it is advisable to send all data at a 1 Hz rate. Otherwise, there might be vehicles entering a portable reference station's coverage area and receive only a partial set of RTCM messages. Hence, in worst case, exact position determination requiring a full set could be delayed up to 9 s.

The ITS-G5 communication architecture offers various configuration options, e.g. for the transport layer's Basic Transport Protocol (BTP) or even more for the network layer based on the GeoNetworking (GN) protocol (ETSI, 2014b). Since Portable Bases exhibit a unidirectional communication pattern, i.e. they do not expect any answers from rovers, the non-interactive BTP-B (ETSI, 2014c) is selected. Complementary, GeoBroadcast (GBC) is a suitable GN routing mechanism for the presented use case. The addressed area by a Portable Base, a circle with radius 5 km centred around its position, is considerably larger than a single station's direct communication range. With GBC, however, neighbouring vehicles equipped with ITS-G5 technology are involved as relay nodes. Availability of these vehicles acting as relays presumed, all rovers

Table 1. Simulation parameters

Parameter	Setting
RTCM interval	1 s
packet length	545 bytes including GN header
network routing	GeoBroadcast (ADVANCED)
destination area	Circular with 5 km radius
packet lifetime	5 s
traffic densities	7 variants (t_1 to t_7) with 51 to 484 vehicles

within the addressed area receive RTK data for individual positioning augmentation. For the exact details of the employed packet forwarding mechanisms refer to ETSI (2014b, appendix E.4).

Sparse traffic densities can be expected in rural areas, especially on cross-country roads connecting towns and villages. Therefore, the effect of a GN feature named Store & Carry Forwarding (SCF) is of great interest. When SCF is enabled for a packet, forwarding nodes are allowed to defer (re-)transmission until an appropriate partner enters its communication range. Therefore, SCF can help to bridge temporary gaps between vehicles, if these gaps are shorter than the packet lifetime. According to RTK's double differences, the age of RTCM data should be below 5 s. Thus the packet lifetime is set to the same value in our analyses. The effectiveness of SCF is thus one aspect studied in more detail in the simulation study. Table 1 summarises the most important simulation parameters.

4. SIMULATION OF DATA DISSEMINATION

Simulation is the preferred way for assessing VANETs because adequate vehicle fleets are usually not available. Furthermore, simulations allow to vary parameters under otherwise identical conditions and study the parameter's influence. Foundation of this paper's simulation study are the traffic simulation SUMO (Krajzewicz et al., 2012) together with the Vehicle-to-X (V2X) simulation frameworks Veins (Sommer et al., 2011) and Artery (Riebl et al., 2015). Latter enables to equip each simulated vehicle with an ITS-G5 protocol stack, in this case the Vanetza (Riebl, 2015) implementation developed at CARISMA.

Traffic is simulated on an approximately 130 km² large map section depicted in Figure 3. This map section has been extracted from OpenStreetMap (2016) and represents the area around Denkendorf and Kipfenberg, quite in the middle of Bavaria. In each of these two municipalities a Portable Base has been placed in its industrial area, indicated by markers ① and ② respectively. The linear distance between both is roughly 5.3 km, i.e. their addressed areas are partially overlapping. All traffic is following randomly generated routes without preference for certain map sections.

Application payload, i.e. RTK data encoded by a Portable Base, is created every second with a length of 485 bytes. This length accounts for RTCM messages with ten GPS and ten GLONASS satellites in view. GBC packet forwarding is studied for addressed areas with 5 km radius derived from aforementioned area coverage deliberation. All results employ the default GBC forwarding algorithm "ADVANCED" (ETSI, 2014b, appendix E.4). Parts of this algorithm depend on knowledge about neighbouring

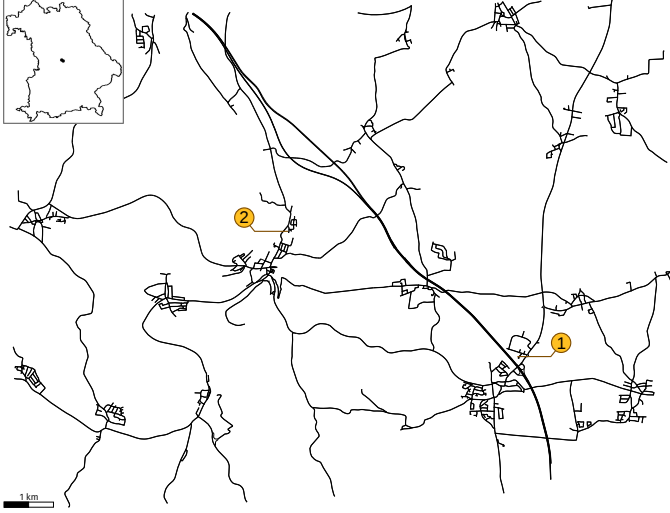


Fig. 3. Map section used for simulation

vehicles' positions and alike. Thus, each V2X capable car stores the sender information contained in received packets in its location table as part of its GN routing procedures. Update behaviour of these location tables is mainly characterised by the reception of Cooperative Awareness Messages (CAMs) because ETSI (2014a) demands all driving vehicles to generate these messages periodically, up to ten per second. Therefore, CAMs are emitted within the simulation according to the specified generation rules. In summary, driving vehicles (rovers) transmit CAMs periodically and possibly receive RTCM packets, whereas parked vehicles (bases) broadcast RTCM packets exclusively. All vehicles can of course act as relay nodes for GBC packets such as RTCM packets.

Recording of each simulation run precedes a warm-up period of 5 s, so location tables and queues are reasonably filled. These 5 s concur with the packet lifetime limited by the temporal applicability of correction data.

5. SIMULATION RESULTS

Results from simulation are assessed by a metric evaluating the effectiveness of the designed CP application. For the purpose of this metric the destination area is divided in annuli of 1 km width centered around the respective source Portable Base. The innermost annulus degrades to a circle with radius of 1 km. $V_{R,B}$ is the set of vehicles v within an annulus, where R is the outer annulus' radius and B identifies the Portable Base. The subset of these vehicles actually receiving RTCM messages is denoted by $V_{R,B}^*$. Vehicles belong to $V_{R,B}^*$ until the end of validity of the last received RTCM message. RTCM data remains valid until its age reaches the upper limit of $T_{RTCM} = 5$ s, as derived in Section 3.2. End-to-end delay induced by the VANET shortens the period in which RTCM information is applicable, because at time of reception the contained information is already of older age. In this context, $\Delta t_{v,B}$ denotes the time span since a vehicle v received the last packet from base B . The ratio of both set's cardinalities describes then the effectiveness $PBE_{R,B}$ of a Portable Base B for its annulus R as defined in Equation 3. Since the number of vehicles attributes the significance of an annulus's effectiveness, the traffic density $D_{R,B}$ according

to Equation 4 is given as well. A_R denotes the area covered by annulus R .

$$V_{R,B} = \{v \mid (R - 1 \text{ km}) \leq d(B, v) < R\} \quad (1)$$

$$V_{R,B}^* = \{v \in V_{R,B} \mid \Delta t_{v,B} \leq T_{RTCM}\} \quad (2)$$

$$PBE_{R,B} = \frac{|V_{R,B}^*|}{|V_{R,B}|} \quad (3)$$

$$D_{R,B} = \frac{|V_{R,B}|}{A_R} \quad (4)$$

$$\text{with } R \in \{1 \text{ km}; 2 \text{ km}; 3 \text{ km}; 4 \text{ km}; 5 \text{ km}\} \quad (5)$$

$$B \in \{1; 2\} \quad (6)$$

The results of simulations with 60 s duration are shown in Figure 4. The upper four charts show the average effectiveness $PBE_{R,B}$ of the five annuli for different starting times (t_1 to t_7), distinguished by SCF setting and originating Portable Base, respectively. The traffic densities of the annuli $D_{R,B}$ are depicted in the bottom row of Figure 4. Areas prone to accidents because of intersections and comparatively high traffic densities are closely located to Portable Bases. In line with the introductory motivation, these most relevant areas are also supplied best, as can be derived from the PBE metric of inner annuli in sparse traffic constellations (t_1 to t_3). More dense traffic pushes only the measurable effectiveness of outer annuli. Nevertheless, the outermost annuli cannot catch up to the PBE of the inner ones.

Although vehicles driving in an outermost annulus cannot be provided with RTCM well by one Portable Base, these vehicles can belong to an inner annulus of another Portable Base simultaneously, as it is the case for the overlapping area of the Portable Bases in the investigated scenario. $PBE_{R,B}$ is always determined regarding a specific Portable Base B and ignores possible receptions from another RTCM source. Therefore, Table 2 presents the overall effectiveness $PBE_{1U...U5,1U2}$, where all vehicles receiving RTCM data from any Portable Base are considered. Since forwarding of RTCM messages relies on other vehicles being in the vicinity, simulation runs tend to achieve better effectiveness results with increasing traffic density.

Table 2. Medians of combined effectiveness $PBE_{1U...U5,1U2}$ [%]

	t_1	t_2	t_3	t_4	t_5	t_6	t_7
w/o SCF	60.0	63.2	67.0	60.7	79.5	69.5	72.7
w/ SCF	58.3	61.9	61.9	70.8	68.4	74.7	68.5

Regardless of whether overall or per annuli effectiveness is studied, enabled SCF is outperformed in most cases by its counterpart simulations with disabled SCF. This observation refutes the initial expectation that the communication's performance should be improved by SCF or the system should operate at least as good as without SCF, especially in sparse traffic. Consequently, the SCF mechanism in its current form has to be denoted as dysfunctional.

Figure 5 illustrates a further issue that needs to be tackled before an IVC application like the outlined RTCM service

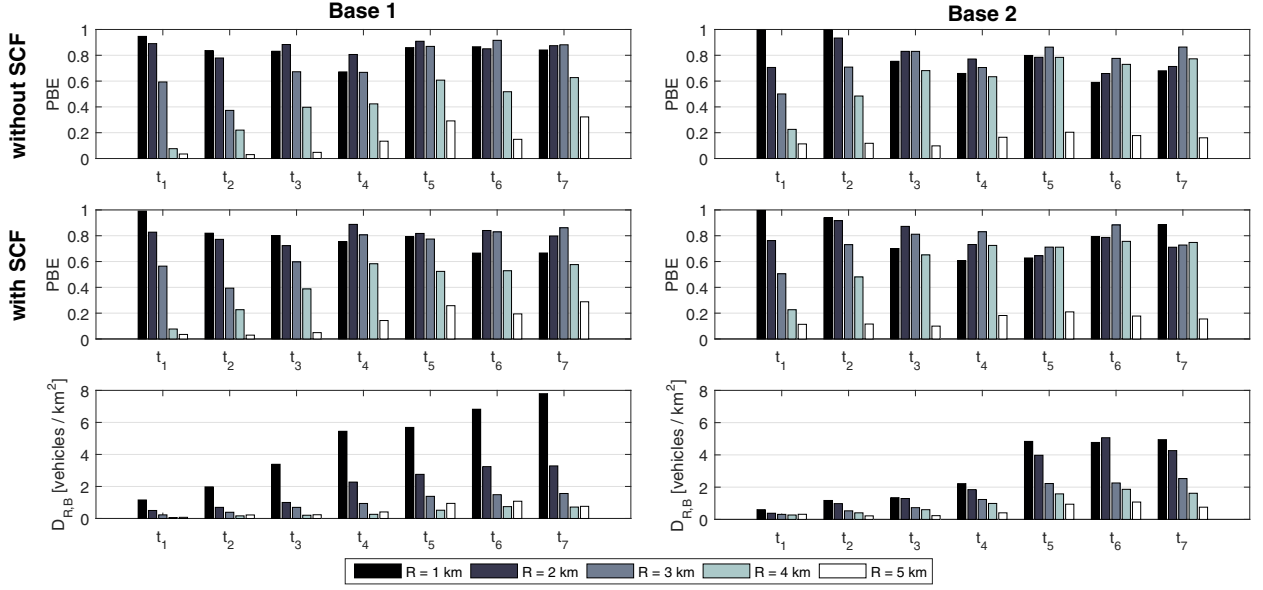


Fig. 4. Traffic densities and PBEs of both Portable Bases averaged over 60s with and without SCF

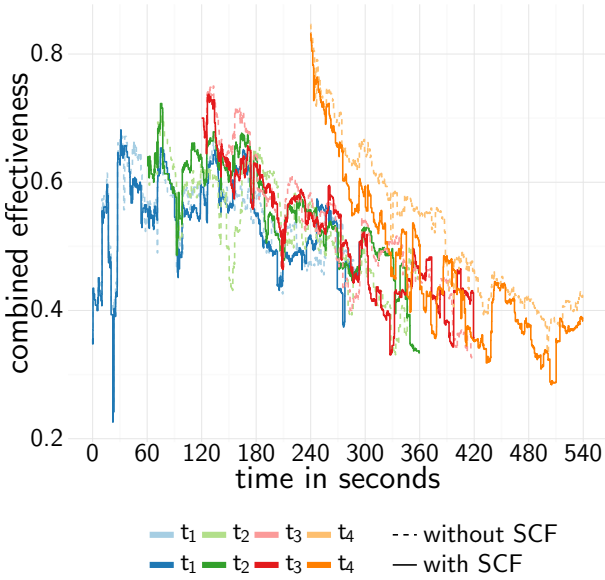


Fig. 5. Effectiveness' derogation

can be deployed based on ITS-G5 protocols. Similar to Table 2 the combined effectiveness is shown, however, with focus on its evolving over 5 min each. There is a noticeable derogation of effectiveness, which becomes more extreme with increasing traffic density. However, traffic density or distribution itself cannot be the reason because the plotted simulation runs overlap partially and equal effectiveness would be expected at same points of time when traffic is identical. Nor reveals simulation data more severe packet drop rates by the Decentralized Congestion Control (DCC) gatekeeper regulating outgoing packet flow of each vehicle. Thus, more elaborate investigations are required to track down the cause for this behaviour, which might have its roots in the employed routing algorithm.

Figure 6 depicts the density of RTCM receptions during the simulated time period of 60s. Regions with colours

shifted towards red are supplied to a better degree over the whole time than bluish regions. Whenever a vehicle has no knowledge of any valid RTCM data, its current position is marked by a grey dot. Permanently missing data manifests as a trace of grey dots, so these traces highlight the blind spots on the map. Most intense reception areas are found close to towns, where several roads meet and thus expose a favourable vehicle distribution obviously. The road connecting the two major towns covered by the overlapping area of both Portable Bases stands out as well. There are only slight deviations between both SCF variants, however, enabled SCF is capable to close some of the blind spots. This is remarkable because enabled SCF does not necessarily perform for every analysed annulus as shown in Figure 4 and Table 2.

6. CONCLUSION AND FUTURE WORK

The presented results suggest that a satisfying data dissemination is achievable for the proposed self-sufficient CP application. Already the placement of Portable Bases solely at industrial areas across Bavaria promises a high coverage. Uncovered areas based on this modest placement assumption could be supplied by vehicles parking elsewhere because the presented method is not linked with specific parking positions. Conveniently, dissemination of positioning augmentation data via IVC works remarkably well in areas with above-average traffic density. Hence, integral safety functions benefit from accurate positioning when dissemination probability and accident risk eventuate similarly.

Nevertheless, the employed network protocols need to be revised for use cases like CP. Performance of GeoNetworking's SCF is disappointing in its current state and the observed derogation of effectiveness remains an unresolved issue yet.

Even with improved network communication RTCM data stream interruptions cannot be prevented at all times, so enhancements to the CP method itself are devisable as well.

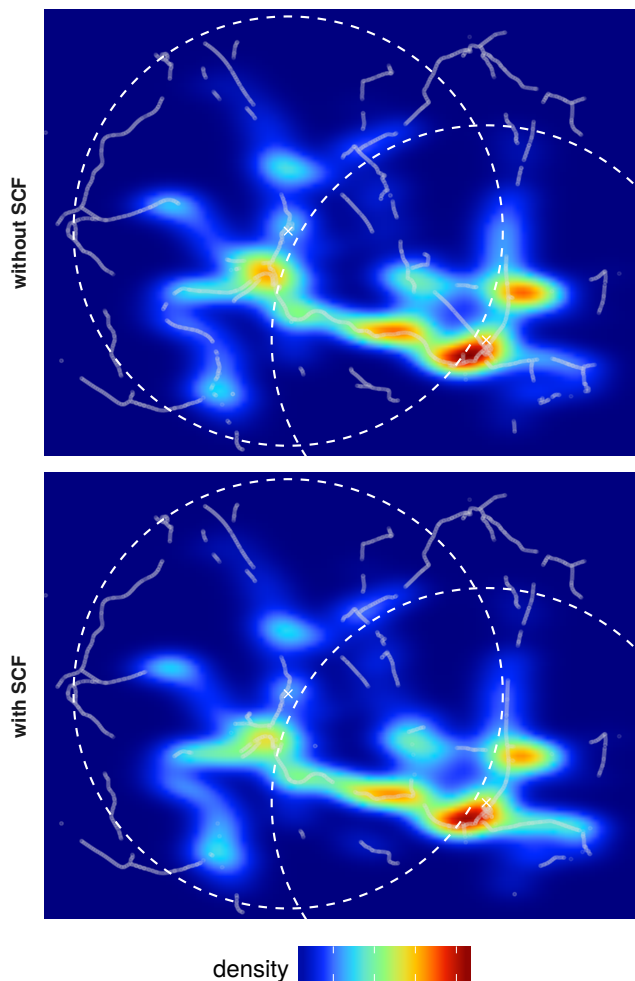


Fig. 6. Reception density and blind spot traces for t_3

Additional techniques for accurate positioning can mitigate these outages, e.g. by using landmarks (Speth et al., 2015). Relative positioning methods operating on the last well known position in the global reference system can alleviate short interruptions, too. However, these also need to provide RTK typical accuracy. For this purpose, sensor data from inertial measurement units or environmental sensors could be used, with which a vehicle might be equipped.

Further limitations arise from adverse parking positions: A parking vehicle with limited sky view should not act as Portable Base, because (a) its obstructed view usually correlates with multipath propagation errors and (b) only a subset of RTK observations is available for dissemination to rovers at all. PPP measurement deviations are another possible link in the chain of errors. Determination of an appropriate confidence threshold or a minimum convergence time of PPP measurements is thus a future task.

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